ARMY RESEARCH LABORATORY

On the Application of Genetic Algorithms for Optimization of RTM Process Parameters

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Abstract

Resin infusion processes are finding increasing applications in the manufacture of composite parts that have geometric and material complexities. In such cases, the placement of gates and vents is nonintuitive and may require expensive repetitive experimentation. Finite element-based resin-flow simulation codes have been successfully used for modeling and analysis of the mold-filling process. Such filling simulations, when coupled with a search algorithm, can also prove useful for optimal design of the filling process. Genetic algorithms (GAs) mimic natural selection and can efficiently "evolve" near-global optimal solutions from a large number of alternative solutions. In this paper, GAs are used to optimize gate and vent locations for the resin-transfer molding (RTM) process in order to minimize fill times and dry-spot formation. A process performance index, or cost function, is defined, which incorporates the fill time and dry-spot formation as primary variables. A part having material and geometric complexities was chosen for a case study. GA and mold-filling simulations were used interactively to search for optimal gate and vent locations to locate near-optimal solutions. The GA was able to find good solutions using less than 1% of simulations of the possible permutations of gates and vents. The case study was also repeated in the presence of racetracking channels. Again, the optimal locations were found by the GA using less than 1% of all possible combinations.

Acknowledgment

The authors gratefully acknowledge the help of Dr. Murat Sozer from the University of Delaware in writing the LBASIC scripts for this work and for his many helpful discussions.

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1. Introduction

Liquid-injection molding processes, such as resin-transfer molding (RTM), are being used in the manufacture of composite structures that have varying material properties in aerospace and defense applications. These processes are attractive, since they enable the manufacture of parts with good strength-to-weight ratio, with material properties tailored to specifications, and in desired "net" shapes.

In RTM, the reinforcement material or "preform" is placed inside a mold. The mold is closed, and the resin is injected into it at high pressure through inlet ports or "gates." Outlet ports or "vents" are used to enable the displaced air to escape out of the mold. The resin impregnates the preform and polymerizes to form the solid part, which is then demolded, as shown in Figure 1 [1]. The manufacture of these complex composite structures by RTM may lead to the problem of "dry spots," which are areas not wetted-out by the resin due to the trapping of air pockets between flow fronts, thus affecting the quality of the manufactured parts. Mold-filling simulations can track the flow-front location during the impregnation of the preform, once the user has specified the locations of inlet gates and vents. However, there are as many choices for gate and vent locations as there are nodes in the finite element (FE) mesh for the mold geometry. To find the globally optimal locations, one would have to run a large number of simulations. This number could be reduced if an appropriate optimization technique were used. Optimization of the filling process is critical, due to the need to decrease the process cycle time and to complete the filling before the resin starts to cure.

For parts having material and geometric complexities, the location of gates and vents is nonintuitive and extensive trial and error is involved in optimizing their position. Hence, there is a need for a systematic search method that can be interactively coupled with filling simulation capabilities to determine optimally placed gates and vents in order to minimize fill times, as well as dry-spot formation. Of the search techniques studied, genetic algorithms (GAs) have been proven as powerful and robust search methods in dealing with highly nonlinear and large spaces

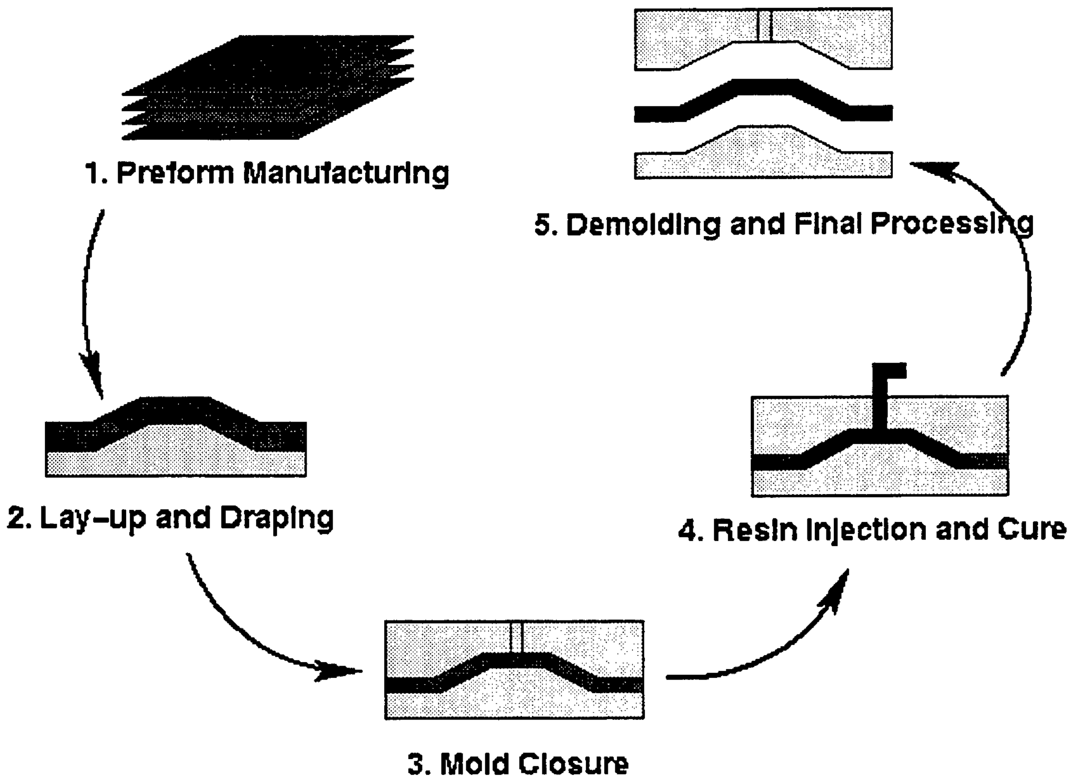


Figure 1. Processing Steps in RTM.

having many possible local optima. In this case, the search space consists of a large number of nodes from FE models and, hence, the number of possibilities is formidable. In addition, with respect to the location of gates and vents, the trends in dry-spot formation and fill time are nonlinear. Hence, GAs were selected as a search method.

In the following sections, some of the pertinent body of work on modeling and simulation of RTM, GAs, and model-based optimization and its application to RTM is reviewed. A description of the operation of a simple genetic algorithm (SGA) is given. The implementation of the SGA with the help of a case study is described, and the results are presented and discussed. It was found that GAs could efficiently locate near optimal gate and vent locations for the manufacture of complex composite parts by RTM, where the optimal locations are not obvious to the designer. The near-optimal gate locations are then used as a starting point to converge onto a globally optimal gate location.

2. Background

The flow of resin in porous media is governed by Darcy's Law, which states that the velocity of a fluid flowing through a porous medium is directly proportional to the driving pressure drop:

$$\vec{u} = -\frac{\underline{\underline{K}}}{\eta}\vec{\nabla}P, \tag{1}$$

where $\vec{u}$ is the average velocity, $\vec{\nabla}P$ is the pressure gradient in the fluid, $\underline{\underline{K}}$ is a second rank permeability tensor, and η is the viscosity of the resin. This can be coupled with the continuity equation for incompressible flow (equation [2]) to give a Laplace equation (equation [3]) for the pressure field inside a fibrous porous media permeated by the fluid:

$$\vec{\nabla} \bullet \vec{u} = 0, \tag{2}$$

and

$$\vec{\nabla} \bullet (\frac{\underline{\underline{K}}}{\eta}\vec{\nabla}P) = 0. \tag{3}$$

This equation can be discretized using FE methods that can be used for simulation of the filling of molds in RTM processes [2–5].

The flow of resin in RTM has been modeled by the discretization of the governing partial differential equation (i.e., equation [3]) using the FE method [2, 3]. The solution involves tracking a moving boundary either using control-volume techniques [4–6] or the movement of a saturation field [7, 8]. Simulation software, such as Liquid-Injection Molding Simulation (LIMS), Version 4.0 [4, 9], uses control volume techniques to simulate the resin flow in

two-dimensional (2-D) molds and in thin three-dimensional (3-D) parts. One may also use the saturation field approach for 2-D or 3-D mold filling. However, the central processing unit (CPU) time is extremely large for 3-D mold filling [10]. Nevertheless, the codes essentially capture the physics of the process. In addition, LIMS can be used to investigate phenomena such as racetracking effects (preferential flow along edges of a mold) and to test control schemes for mold filling [11].

Usually, the geometry; material parameters; gate and vent positions; and pressure or the flow rate, or a combination of the two, are specified before the filling simulation is carried out. The simulation code is used to track the location of the flow fronts, estimate fill times, and account for racetracking effects. In addition, LIMS is capable of showing dry-spot formation and tracking of dry spots as filling progresses [11]. Such flow simulations have also been used to study the effects of different configurations of gates and vents on mold filling, wherein the process inputs are already fixed.

During the filling process, the area of the preform that is poorly wetted-out, or not wetted at all, by the resin, is called a dry spot. Dry spots have been investigated and classified both experimentally and numerically [12, 13]. It has been shown that the positioning and control of gates and vents can lead to dry-spot reduction [11].

The optimal placement of gates and vents and cure-cycle optimization have been carried out using GAs [14, 15]. The method employed used a cost function that is comprised of the maximum difference in times at which the resin reaches the boundary of the mold. This was a measure of the uniformity of filling and, indirectly, of dry-spot formation. However, frequently, the inlets or "gates" are to be located on the edges of the mold and this cost function cannot be used since the resin is injected at the edges. In addition, the locations of gates and vents are dependent on each other in a complex and nonlinear fashion. The present study explicitly defines gate and vent locations and formulates a cost function that accounts for the size of the dry spot and the fill time. These are coupled with the GA and the filling simulation to carry out the optimization of gate and vent locations.

3. Optimal Design and GAs

3.1 Optimization of Design. Optimal design can be defined as the selection of the best set of inputs for a process to meet certain requirements using available resources. Design optimization proceeds in the following phases: recognition of needs and requirements (problem definition), creation of one or more design configurations (synthesis), the study of the configurations' performance using engineering science and knowledge (analysis), and the selection of the "best" alternative (optimization). The design is defined as a system of design variables, parameters, and constants. The optimal design is selected using a criterion that is called an objective function. The objective function is sometimes referred to as a cost function since a minimum cost is often desired [16].

The selection of an optimal design is usually an iterative process involving a search technique that searches for the "best" design configuration. A mathematical model of the system is used for evaluation of the objective function for each design configuration. The mathematical, or simulation-based, model is a numerical representation of the relationship between process inputs and process outputs. For example, the filling simulation is a very sophisticated model that relates the inputs (e.g., gate and vent positions, permeability data, injection pressures, etc.) to the outputs, such as fill times, pressure fields, and dry-spot formation and location.

As illustrated in Figure 2, the process of optimal design for RTM involves the coupling of a cost function, which incorporates the important criteria for optimal design with a filling simulation. The variables to be optimized are gate and vent positions in order to minimize the fill times and area dry-spot formation.

Conventional search techniques are gradient-based. The gradient of the objective function with respect to the design variables is evaluated, and the variables are adjusted along the line of maximum slope until a minimum is reached, where the gradient is zero. Gradient-descent-based techniques tend to get trapped in local minima and strongly depend on an initial guess and on the existence of derivatives.

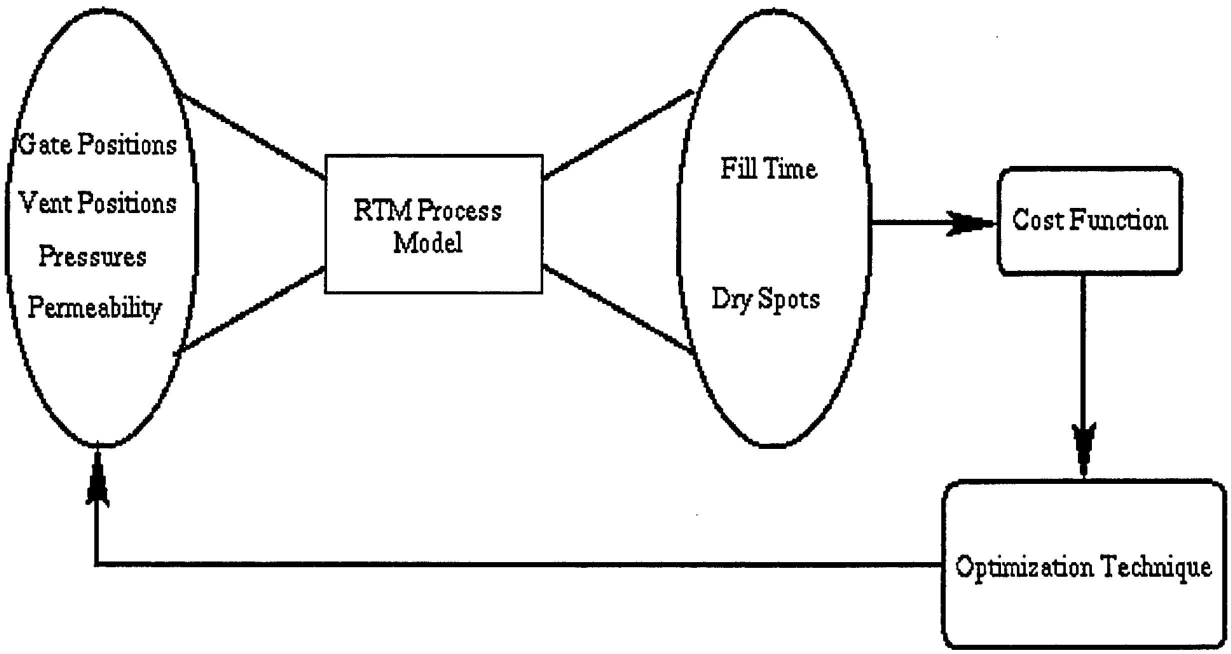


Figure 2. Schematic of Optimal Design for the RTM Process.

GAs are search algorithms that mimic natural selection and genetics to "evolve" the best solution to a problem from a large number of alternative solutions. The solution is usually represented by a binary string. A sample set of solutions, or a "generation," as represented by their strings is evaluated and fitness values are assigned. Two of the strings are selected at a time and "reproduced" using crossover and mutation operators that are defined mathematically, and they produce two new strings or "offspring," until a new set of strings or a new generation is produced. The probability of selection is proportional to the fitness of the string. Hence, the "fittest" strings have a greater chance to contribute to the next generation, imitating Darwinian evolution. The next generation is again evaluated and reproduces. The cycle is repeated until a generation having many good solutions emerges [17].

GAs have proven to be robust and powerful techniques for search and optimization. GAs search from a population of points and use payoff or fitness information with probabilistic transition rules. They generally produce near-global optimal solutions in large search spaces. As illustrated in Figure 3, for a multimodal function (i.e., a function possessing multiple peaks) a gradient-based search method will probably settle on a lower peak (i.e., a local optimum), while

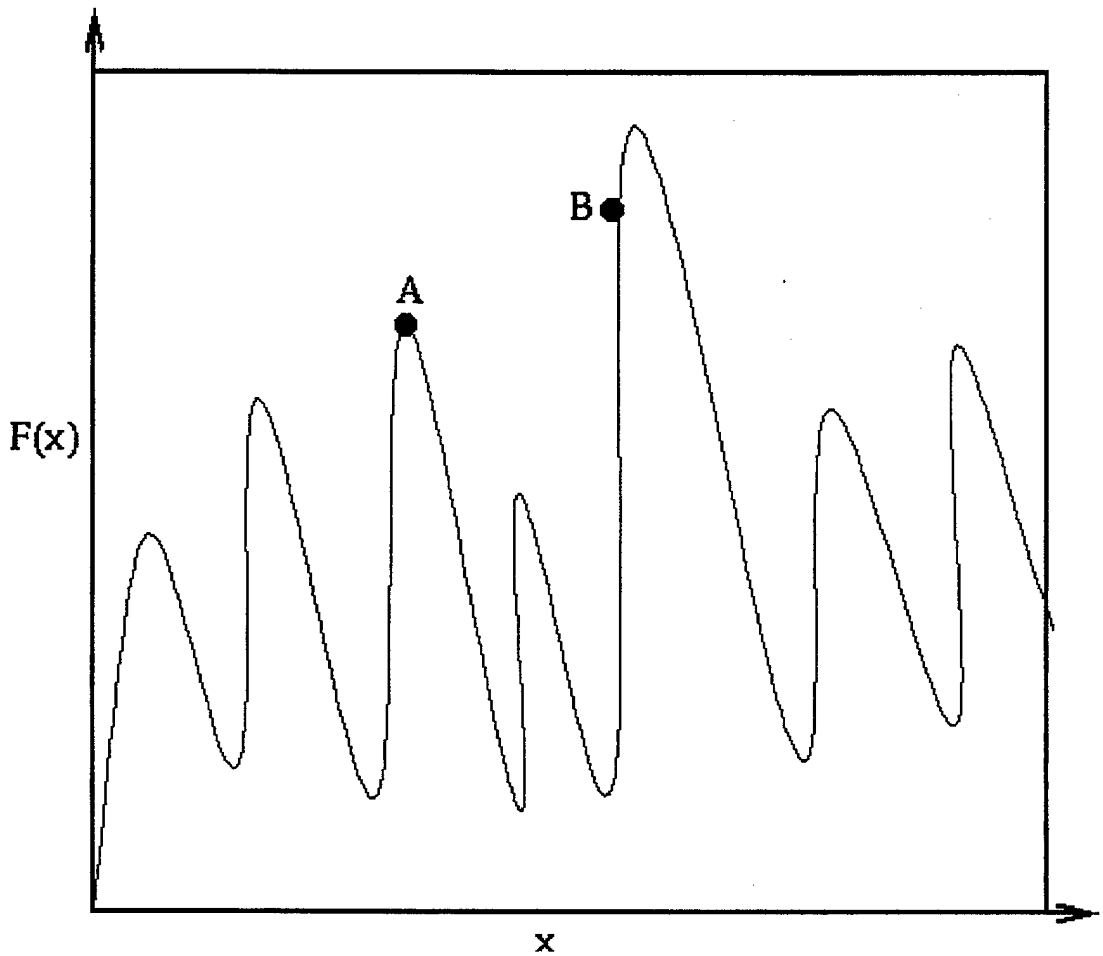


Figure 3. A Function With Multiple Peaks: A Gradient-Based Method Is Likely to Find the Local Peak at Point A, While a GA Will Settle on Point B, Near the Global Maximum.

a GA is most likely to find a point close to the absolute maximum. This is because GAs use information from multiple points in parallel to explore the search space. An SGA has been implemented in this work [18].

3.2 SGA Procedure. The SGA is a powerful yet simple search technique that involves partial swapping and copying of binary strings, which are representations of the optimization variables. The variables themselves can be continuous or discrete, since they are mapped to binary strings. Each string has a "fitness" value, f, associated with it. The SGA employs three operators: reproduction, crossover, and mutation.

The reproduction operator operates on the strings of each generation to produce the strings of the next generation. The strings are allocated space on a roulette wheel, with the size of the sector assigned to each string on the circle, being proportional to its fitness. Thus, the roulette wheel is biased in favor of the "fittest" members of each generation. The wheel is spun, and strings are selected two at a time. These two strings are operated on, by the crossover and mutation operators, to produce two new strings, which belong to the next generation. New strings are produced until the population size (i.e., the number of strings in each generation, which is a fixed number) is attained. This new generation is evaluated, and fitness values are assigned to each member of the generation. A schematic of this process is shown in Figure 4.

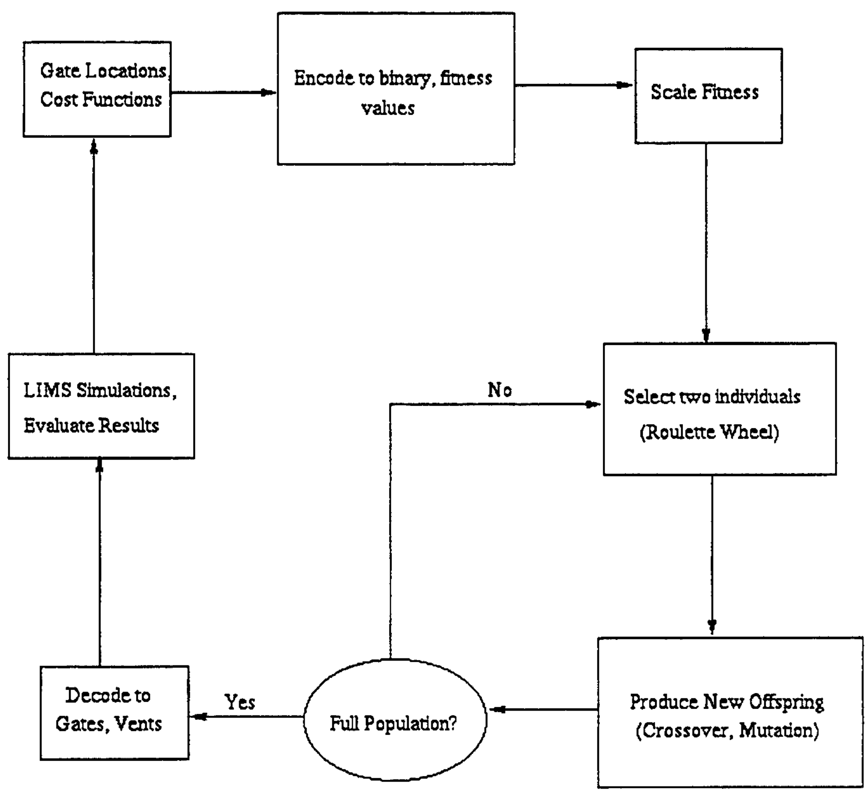


Figure 4. Schematic of LIMS-Based Optimization Using GAs.

The crossover operator takes each pair of strings selected by the reproduction operator to produce two new strings. It does this by randomly selecting an integer position on the string, dividing each of the strings at that position, and then swapping the substrings. If the strings (S1

and S2) are each of length L, a position $k < L$ is selected and the two strings are divided into four substrings, two of length k (s1 and s2) and two of length L-k (r1 and r2). The two new strings are s1-r2 and s2-r1.

The reproduction and crossover operators work in tandem to use high performance strings having high fitness values and generate better strings having higher fitness values, thus emulating natural selection, which favors "survival of the fittest." The mutation operator works by taking the new strings produced and randomly flipping over a few digits from 0 to 1 or 1 to 0. This ensures genetic diversity by producing strings that contain new material and are not totally derived from the previous generation. The three operators are illustrated in Figure 5.

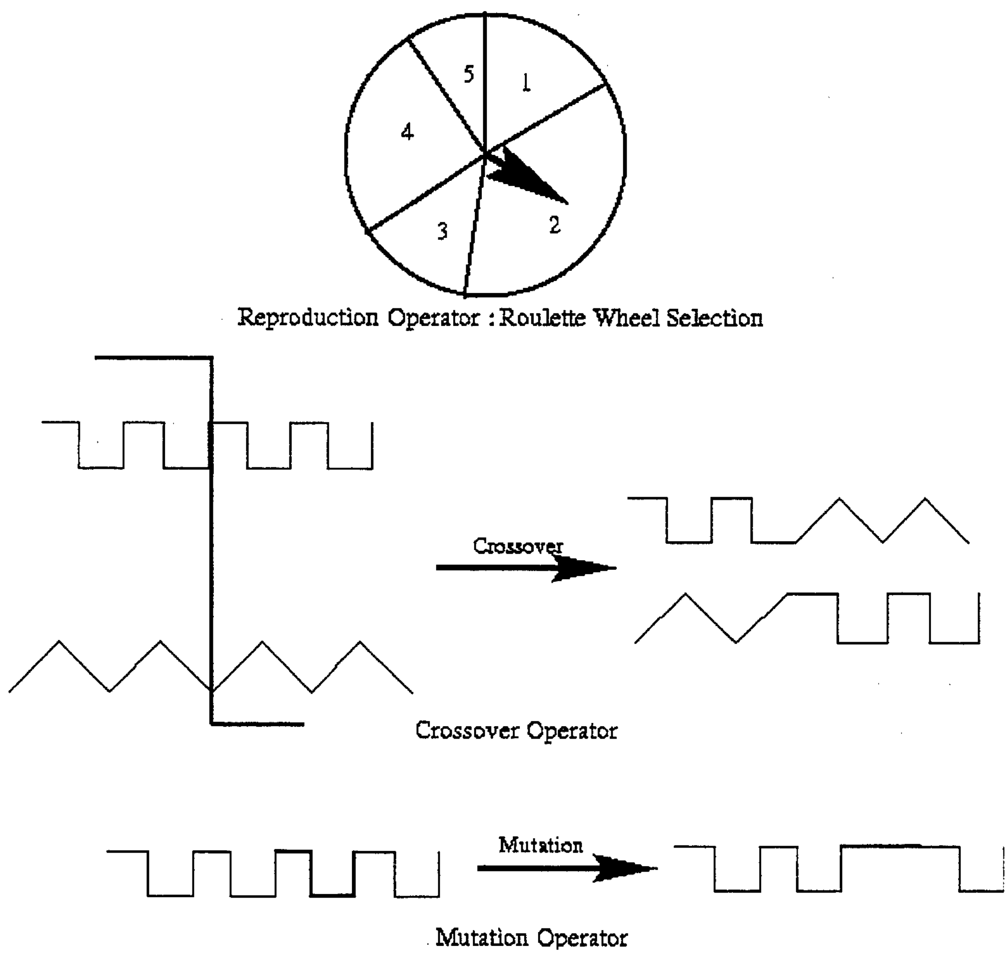


Figure 5. Reproduction, Crossover, and Mutation Operators in GAs.

In terms of optimization and search, the SGA works by searching from multiple points in the search space. It is a random-search technique possessing some degree of determinism. This ensures that the algorithm does not get trapped in local optima. The mutation operator ensures that the search is not localized to a small part of the search space. Since there are no requirements on the fitness function, it allows a high degree of freedom in constructing the function. It has been shown that the SGA will usually locate near-global optima in the search space [18].

3.3 Application of SGA to Gate and Vent Location Optimization. To illustrate the potential and use of GAs, a composite part having material and geometric complexity was used for the case study. This part is a 2-D approximation of a vehicle bed with wheel wells. It is a large planar part and contains a thick section that provides a path of high resistance to the resin. The search space of possible gate and vent locations was defined. An objective function or process performance index (PPI) was formulated, which incorporates the fill time and dry-spot formation, with appropriate normalized weighting factors.

LIMS 4.0 [11] incorporates the LBASIC script language. A script was written to simulate the filling process with sets of gates and vents arranged in a sequential manner and that abandon the filling simulation when a tolerance on the fill time and dry-spot area is exceeded. Initially, a random set of configurations is evaluated using LIMS and the objective function. The SGA, coded in C++, was then used to generate successive sets or "generations" of configurations, with the LIMS-based simulations supplying the cost information for each set. It was observed that the average costs for successive generations showed a decrease, and several optimal configurations were obtained.

The optimization problem solved here, is that of finding optimal gate and vent locations to minimize fill time and dry spot formed for the selected mold geometry and material parameters (Figure 6). The composite part has thicker sections at the center corresponding to the wheel wells. The permeabilities of the preform material are $K_{11} = K_{22} = 10^{-7}m^2$ for the thin section and two orders of magnitude lower, $K_{11} = K_{22} = 10^{-9}m^2$, for the thick section.

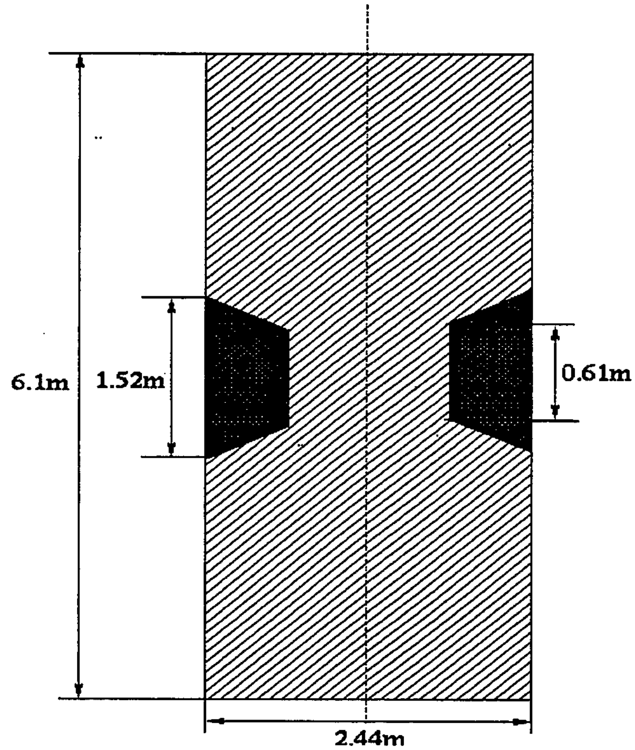


Figure 6. Planar Approximation of the Bed of a Vehicle or Trailer Used for Optimization.

The injection at the gate is performed under constant pressure, which was chosen to be 10 atm at each gate (i.e., a standard injection pressure for RTM of vinyl-ester resins). The vents are at atmospheric pressure. The resin viscosity was chosen to be 0.231 Pa-s, which is a typical value for vinyl-ester resin. The mold geometry was discretized using the PATRAN FE preprocessor [19].

The optimality criterion was represented by the following objective function that is to be minimized:

$$J = \lambda_1 \frac{t_f(1+99H(t-t_{f,tol}))}{t_{f,\max}} + \lambda_2 \frac{\%Void(1+99H(\%Void-\%Void_{tol}))}{\%Void_{\max}}. \tag{4}$$

The PPI formulated incorporated the importance of fill time and voids, although one may include other outputs if necessary. Voids or dry spots are represented by the number of unfilled nodes in the FE model at the end of the simulation. The functions $H(t-t_{f,tol})$ and

$H(\%Void - \%Void_{tol})$ are Heaviside penalty functions, which add a penalty if tolerance limits on time and void formation are exceeded. The variables λ_1 and λ_2 are weighting factors that can be adjusted according to the relative importance of each term. The tolerance time is usually less than the time to initiate gelling and the tolerance on void formation is less than a fraction of a percent for structural applications and a few percent for nonstructural applications.

The optimization problem was attempted for case (a), the ideal case of two gates and vents everywhere (i.e., no vents specified, hence, no dry spots are formed, so the objective function was limited to fill times only); case (b), two gates and one fixed-vent location; and case (c), two gates and four vents. Since the mold geometry has left-right symmetry, the flow in only the left section with one gate specified considered. In case (c), there are two vents in the left section placed symmetrically about the centerline; hence, only one vent needs to be independently specified. The search area was initially restricted to the boundary of the mold, which was divided into 128 parts; as in many cases, the mold is held in a press and it is generally costly to inject from the top or the bottom face. Each gate or vent location corresponds to a node in the FE mesh and is represented by a seven-digit binary number. Hence, the gates in cases (a) and (b) are represented by seven-digit binary strings in the GA. In case (c), the gate and two vents are represented by two seven-digit strings joined together.

The worst case for filling is with one gate at the center of the thick section with fixed vent location. The fill time is 62,979 s with 638 unfilled nodes. It was observed that, in case (b), the fill times in the first generation were distributed with 75% of the cases having fill times below 6,500 s and, in case (c), fill times were below 9,500 s. The values of the weighting factors were $\lambda_1 = 10$ and $\lambda_2 = 5$; and were chosen so that both terms in the cost function have equal importance.

In each case, an initial population of 6–8 strings was generated randomly. These were decoded to gates and vents and the mold-filling simulations were performed using the LBASIC script. The cost function was evaluated. The GA uses the cost function to calculate the fitness of each string, using the linear scaling function, *fitness(x)* = 1,000−*cost(x)*, and produces the next

generation, which is decoded and evaluated. This optimization loop was continued for several generations, until the average cost function over each generation was below a preset value.

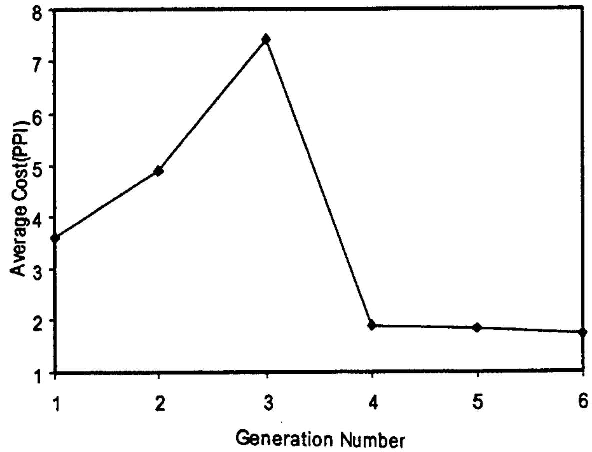
3.4 Optimization With Racetracking Effects. Racetracking channels are created when there is a gap between the preform and the mold wall. The channels provide a path of least resistance to the flow and dramatically affect the flow-front movement of the resin in the mold. Thus, the optimal locations of gates and vents to minimize fill time and dry-spot formation, as previously defined, will change.

In the previous study, the boundaries of the mold were considered for the location of gates and vents. In this study, with racetracking effects included, the boundary cannot be the location of both a gate and a vent, since the mold will not fill as the racetracking channel provides a conduit of least resistance from the gate to the vent. However, if one of them were to be located on the mold boundary and the other in the center of the mold, then there exists a possibility for the mold to fill. Hence, for this study, the centerline of the mold was also included in the search space. The geometry on this case study was identical to the previous one, except that a racetracking channel of width 2.54 cm and depth 0.64 cm around the boundary of the mold was incorporated into the FE model of the mold. The total number of possible nodes that could serve as a gate or vent was 304. The optimization problem was solved for the case of two gates placed symmetrically about the centerline of the mold and a single vent placed on the centerline of the mold. Each configuration was represented by a 15-digit binary string, where the first 8 digits correspond to the gate, which can be anywhere on the racetracking channel and the centerline, and the last 7 bits represent the vent, which is restricted to the centerline.

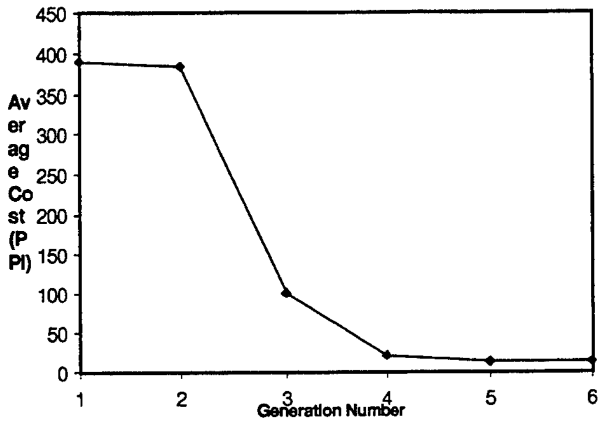
4. Results

The GA was first applied for the three cases without the racetracking effect, as described in the previous section, with five to six generations being evolved in each case. The average values of the cost function per generation are plotted in Figure 7. The best configurations are shown for each case in Figure 8.

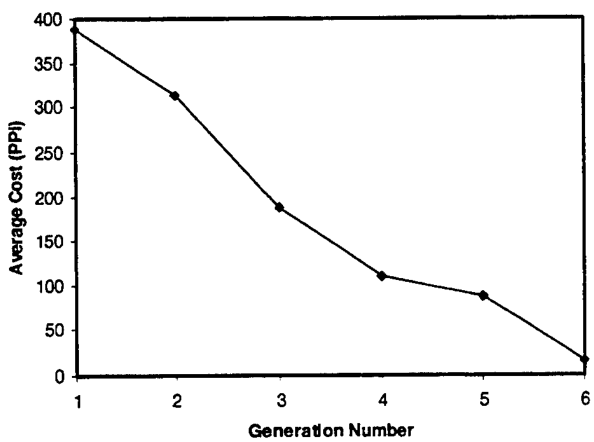
Case (a)



Case (b)

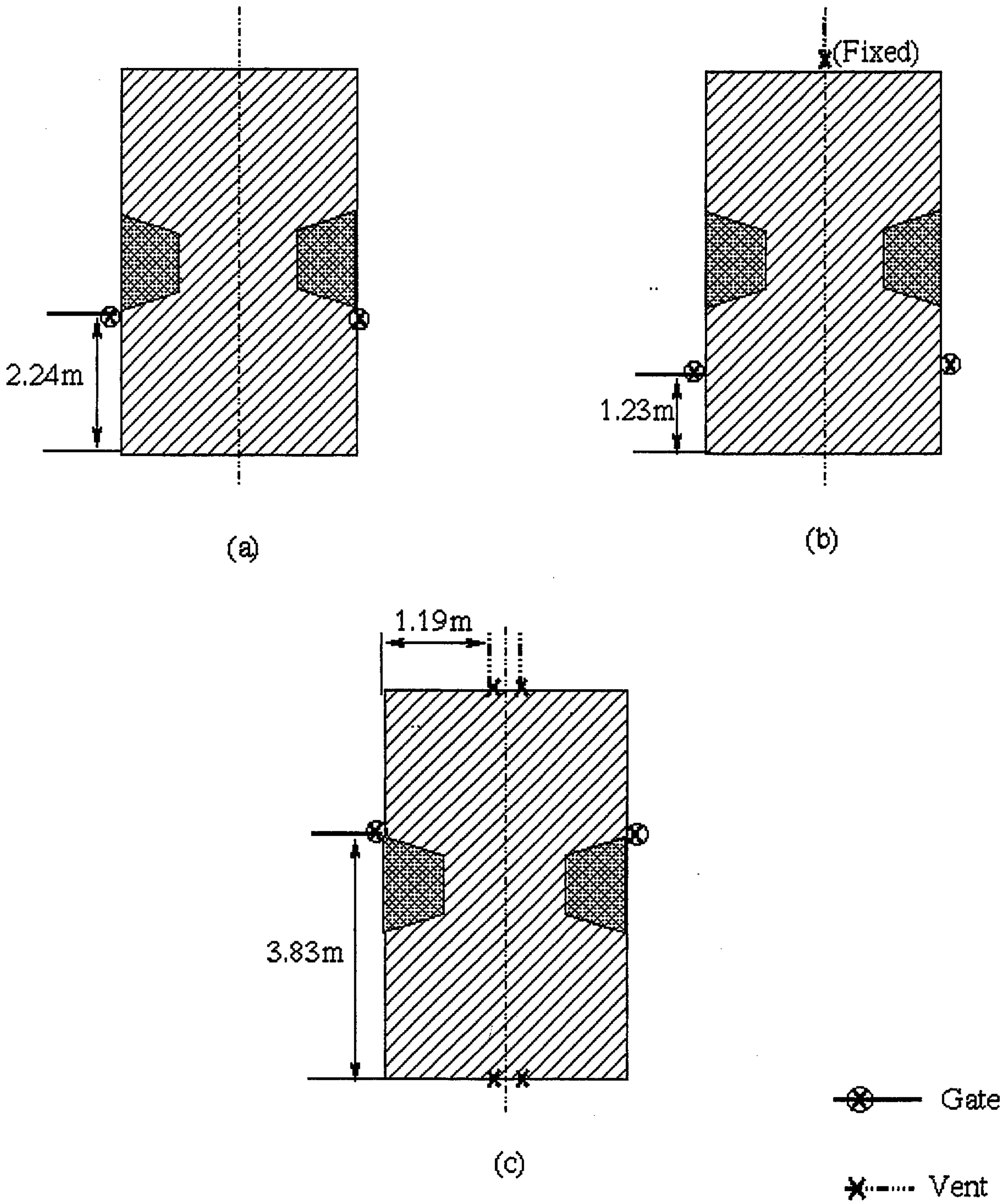


Case (c)



Note: Case (a): Two Gates, Vents Everywhere.
Case (b): Two Gates, One Fixed Vent.
Case (c): Two Gates, Four Vents, No Racetracking.

Figure 7. Plot of Cost Function With Generation Number for Each Case.



Note: Case (a): Two Gates, Vent Everywhere, Fill Time = 3,292 s.
Case (b): Two Gates, One Fixed Vent, Fill Time = 4,291.6 s.
Case (c): Two Gates, Four Vents, Fill Time = 4,407 s.

Figure 8. Optimal Gate and Vent Placement for Each Case.

In case (a), when it is assumed that the vent is present everywhere, the average value of the cost function was 3.62 for the first generation and 1.82 for the sixth generation. The best time to fill was 3,290 s, with the gate being located next to the thick section. This makes sense and can be explained as follows: the optimal gate location is as close to the centerline of the part as possible since the resin has to travel the minimum distance. But the thick section is located at the center of the part, and a gate location in the thick section would require a very high time to fill since the flow is at constant pressure and will be forced to go through the high resistance to flow in the thick section. Hence, the optimal gate location is at the edge of the thick section. The number of gates evaluated was 16 out of a possible 32.

In case (b), the gate was allowed to float along the edge of the mold and the vent was fixed at the position shown in Figure 8(b). The average cost value decreased from 390.7 to 12.9 in five generations. The best solution was calculated to take a fill time of 4,292 s and unfilled nodes = 23 or 0.008% dry-spot formation. The number of gates evaluated was 25 out of a possible 128.

In case (c), the vent was free to move in addition to the gate location. The average value of the cost function, as expressed in equation (4), decreased from 388.3 to 14.23 in six generations. The best solution was fill time = 4,407 s, unfilled nodes = 17 or 0.006% dry-spot formation. The number of gate and vent configurations evaluated were 40 out of a possible 16,256 gate and vent configurations. One can see that, as the number of possible configurations increased, the utility of the GA becomes evident, as it was able to locate an optimal solution with fewer than 1% possible evaluations. The vent location was very close to the line of symmetry. A local search showed that the vent should be at the symmetry line, as shown in Figure 8(c).

5. Racetracking Study

In the racetracking study, from 83,000 possible configurations, the GA took 6 generations and 48 simulations to arrive at a near-optimal solution. The average cost function decreased with successive generations and is plotted in Figure 9. Two optimal solutions were obtained that minimized the time to fill and low dry-spot formation using just 0.14% of possible evaluations.

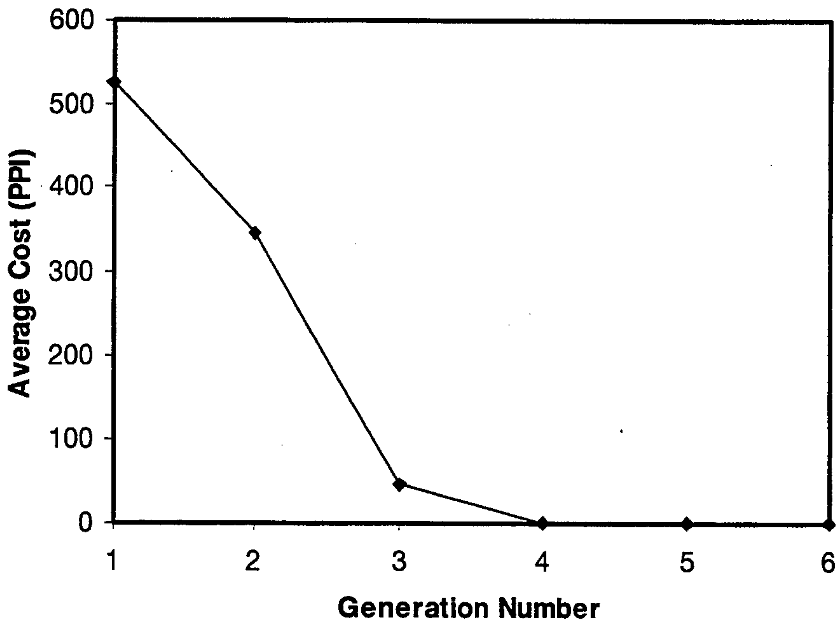
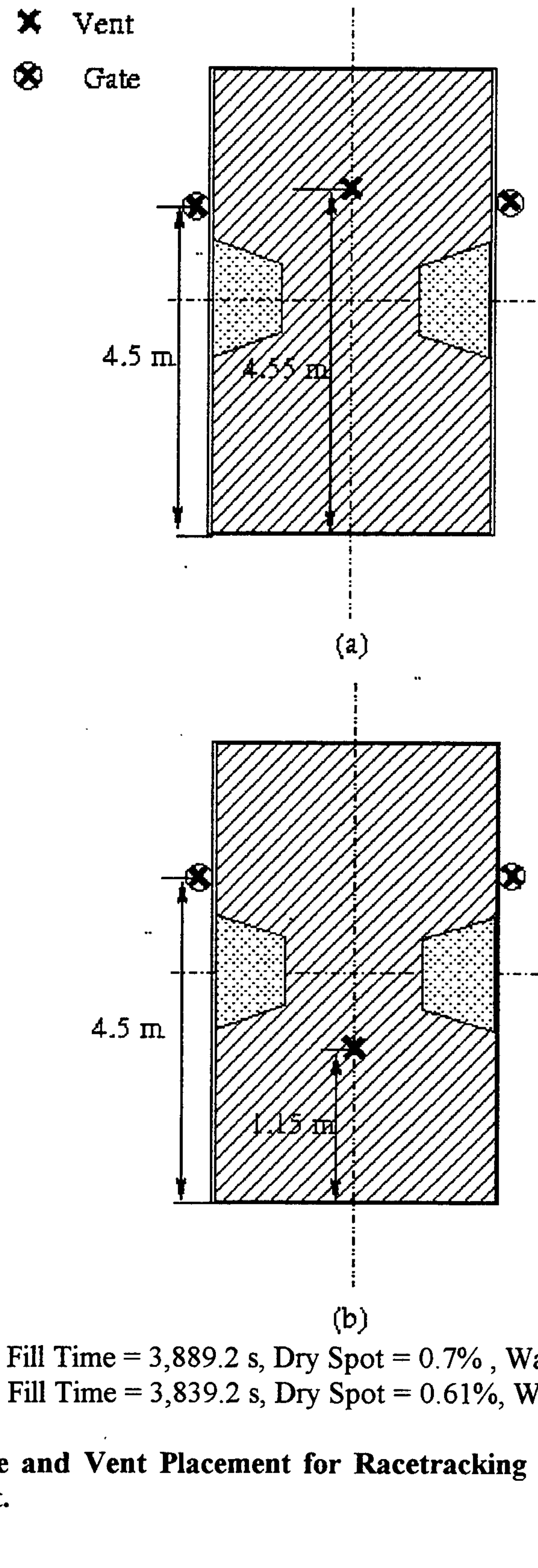


Figure 9. Plot of Cost Function With Generation Number for Racetracking Study.

These are shown in Figure 10. The optimal fill times are much less than those in the case without racetracking channels. The flow contours for the best gate and vent configurations are plotted in Figure 11.

In the previously mentioned case study, the simulation of resin flow in the mold was stopped at a critical time, reflecting the need to complete the mold filling in a finite time, which may be dependent on cycle time requirements, or gel on time of the resin. However, it may be imperative to fill the mold completely in order to obtain good-quality parts. Thus, the resin injection has to be continued for some time until the mold filling is complete. Since the thick section is the last to fill and the vent here is in the thin section, there will be considerable resin wastage through the vent.

The continuous injection was undertaken for the best configuration of two gates and a vent. The mold was filled in 5,309 s (i.e., 20% more time than the 3839.2 s previously considered). The amount of resin wasted through the vent increased to 20% of the total inflow through the gate.



Note: Case (a): Fill Time = 3,889.2 s, Dry Spot = 0.7% , Wastage = 6.0%.
Case (b): Fill Time = 3,839.2 s, Dry Spot = 0.61%, Wastage = 6.7%.

Figure 10. Optimal Gate and Vent Placement for Racetracking Study With Two Gates and One Vent.

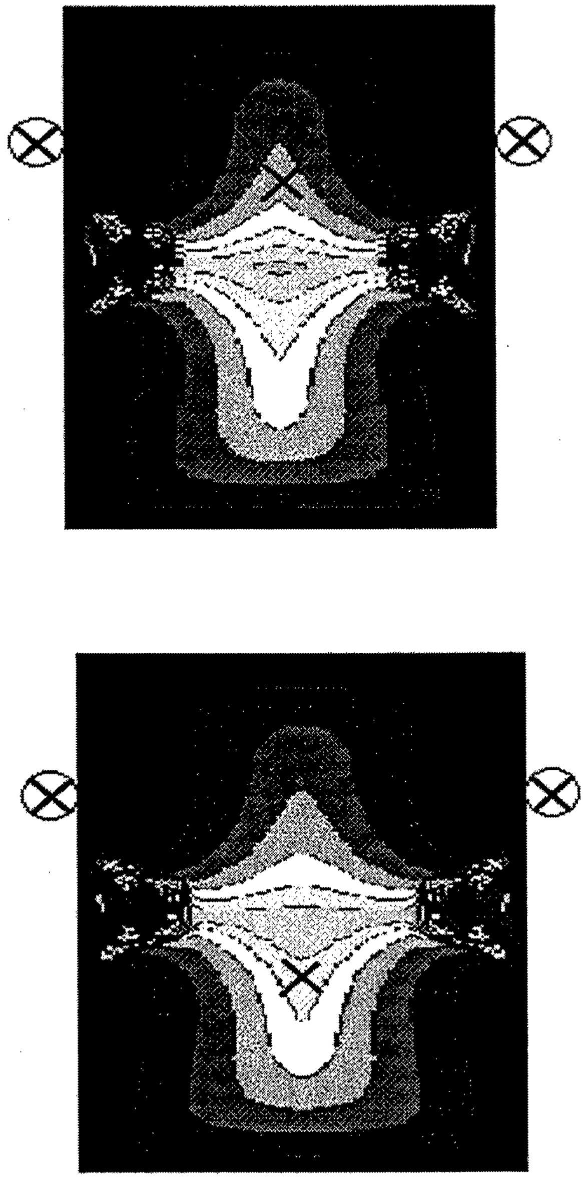


Figure 11. Flow-Front Locations With the Optimal Gate and Vent Locations for the Racetracking Case Optimized by the GA.

6. Discussion

For the case with no racetracking, when a vent is present in the mold and once the resin reaches the vent, it tends to flow from the gate into the vent, as that is the path of least resistance. Hence, if the vent is in the proximity of the gate, then this path is established quickly and the time to fill will be high due to the leakage of resin through the vent and/or with large dry spots

being formed. Thus, the optimal gate location will involve a trade-off between maximum distance between gates and vents and minimum distance from the centerline. This is reflected in the best gate and vent locations determined by the GA for cases (b) and (c).

It was observed that the average value of the cost function decreased with succeeding generations in each case. A number of possibly optimal solutions for each problem were generated. The number of simulations required before the GA found optimal points was much less than the possible number of simulations.

6.1 Racetracking Case. For the case with racetracking, the best gate locations should be placed on the racetracking channel, while the best vent locations should be placed close to the center of the part. This is because the resistance to the flow of resin is the least when it is on the empty racetracking channel. When the gate is on the racetracking channel, it fills quickly, due to low resistance, and acts as a gate. The resin reaches the vent rapidly and then flows through it. This leads to an undesirable quantity of waste resin. Hence, the vent has to be as far away from the racetracking channel as possible. The optimal gate and vent configurations generated by the GA reflect this behavior (Figure 11).

6.2 Resin Waste Through Vent. In the present study, it was observed that there is waste due to the flow of resin through the vent. It can also be seen from the flow contours that the last point to fill is in the thick section, due to its low permeability and a very high resistance to flow. The question arises whether a single vent in each of the thick sections will eliminate the waste of resin altogether as this is the last point to fill.

However, a vent is introduced into the mold in order to allow the entrapped air in the mold to escape. In a large and complex mold, there will be many areas where the air can be entrapped. In the mold considered here, air pockets will form not only in the thick section, but also along the centerline, at the intersection of the two flow-fronts. Hence, if the vent on the centerline were to be eliminated, a dry spot would form in the center of the finished part. However, a vent in the thick section is necessary, in any case. An issue that arises is that of minimizing the resin waste. This minimization is implicit here because, if a greater amount of resin were wasted due to the

suboptimal placement of the vent, the fill time would be higher. Hence, the cost function reflects this and the best configurations obtained here have low resin waste (Figure 10).

7. Further Refinement: Finding Global Optima

The GA here has proven adept at finding good configurations of gates and vents to minimize the fill times and areas of dry spots formed. However, the GA is a search technique that has incorporated an element of randomness. This randomness and the fact that it is a multipoint search technique enables one to quickly find points of interest (i.e., good configurations of gates and vents). For this same reason, these configurations are likely not to be global optima (i.e., the absolute minimum) that one could obtain using an exhaustive search through the thousands of possible configurations. Indeed, GAs have been shown to find near-global optima, when applied to well-known optimization problems. Hence, it is likely that the configurations obtained here lie close to global optima (as in Figure 3). The results can be further refined using a local search technique, such as an exhaustive search or a gradient search, and better configurations can be discovered with very little computational cost. In addition, physical insight obtained from the analysis of the gate and vent configurations can be used for further experimentation.

In the case with no racetraking and dealing with the optimal placement of two gates and four vents, the best solution obtained has the gate near the thick section, while the vents are very close to the centerline (Figure 7). Thus, the globally optimal solution would be to have a vent at both ends of the centerline and the gates near the thick section.

In the case with racetracking, it can be seen from the flow contours that the best vent locations are close to the center of the part, while the gate locations are again close to the thick section. Since the racetracking channel is also present there, the gate can be placed on the portion of the racetracking channel near the thick section. Hence, the globally optimal solution will be to have the gate at the center of this portion and the vent at the center of the part. A simulation of this configuration yields a time of 3,555 s to fill 99.4% of the part (i.e., a dry spot occupying 0.6% volume was formed), if the filling is stopped at this point. This optimal configuration is likely to have been found if the cost function severely penalized the resin

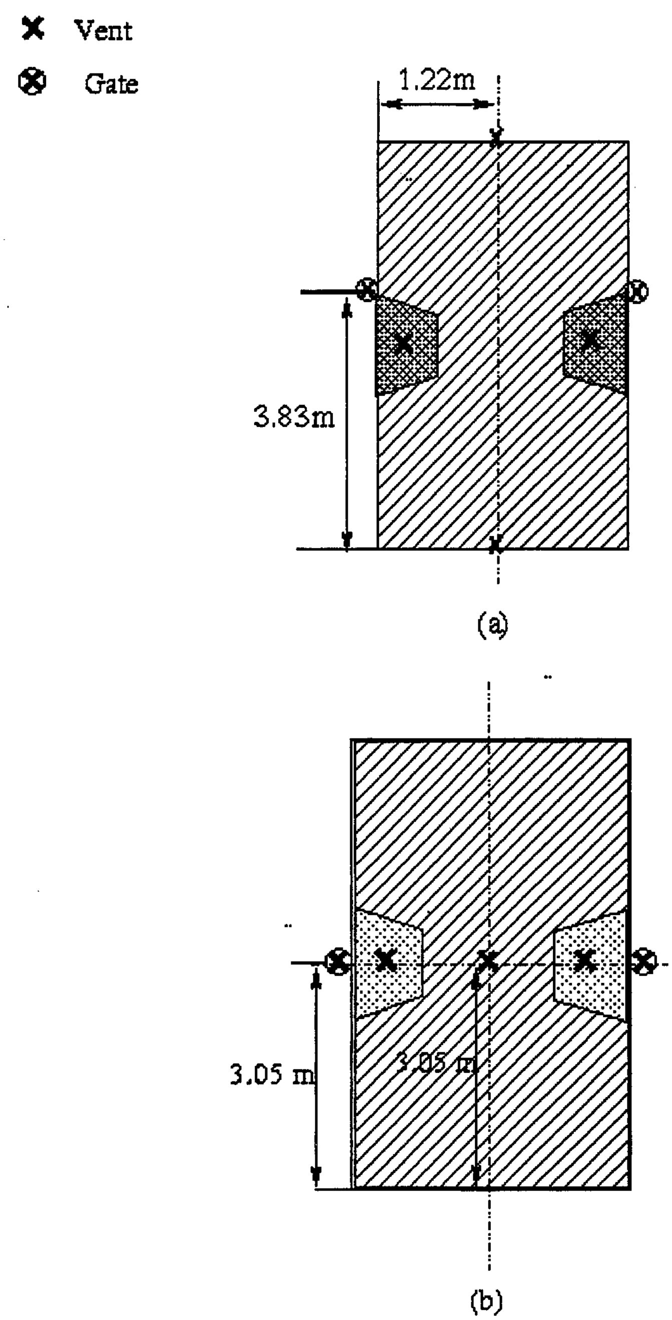
wastage. Continuing the filling process, it takes 5,561 s to completely fill the part with 17.1% of the resin wastage. The global optima for both cases (with and without racetracking) are illustrated in Figure 12. Since the points to fill last are always in the thick section, it may also be necessary to have a vent at its center.

8. Conclusions

To determine optimal location of gates and vents, so as to reduce fill times and improve part quality, is a nonlinear problem for the design of molds for RTM, for the manufacture of composite parts with geometric and material complexities. The solution of this problem requires extensive experimentation on a trial-and-error basis.

A simple GA coupled interactively with finite-element-based simulations has been used as an effective search technique for determining optimal gate and vent configurations, which minimize fill times and dry-spot formation. A PPI was formulated, which incorporates fill time and dry-spot formation directly, with penalties for exceeding performance tolerances. The case study was extended by adding channels that introduce racetracking effects. The solutions obtained made physical sense and can be easily improved using a local search technique.

The approach used here can be applied to obtain solutions to mold design quickly, where the placement of gates and vents may be nonintuitive. The search space can be restricted to a small part of the mold where the placement of gates and vents is feasible. A cost function can be defined, which reflects the process requirements and penalizes bad performance. A GA is an efficient and practical tool, which can determine good configurations of gates and vents from a large number of possibilities. The analysis was carried out by coupling the GA with our mold-filling simulation software, LIMS. The analysis of these configurations and the improvement of the solutions yields valuable insight into the placement of gates and vents in the mold. This would reduce expensive mistakes during the manufacturing of the composite part.



Note: (a) No Racetracking Channel, Fill Time = 4,407 s, Dry Spot = 0.006%.
(b) Racetracking Channel Incorporated, Fill Time = 3,555 s, Dry Spot = 0.6%.

Figure 12. Improved Optima for the Placement of Gates and Vents.

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13. ABSTRACT *(Maximum 200 words)*

Resin infusion processes are finding increasing applications in the manufacture of composite parts that have geometric and material complexities. In such cases, the placement of gates and vents is nonintuitive and may require expensive repetitive experimentation. Finite element-based resin-flow simulation codes have been successfully used for modeling and analysis of the mold-filling process. Such filling simulations, when coupled with a search algorithm, can also prove useful for optimal design of the filling process. Genetic algorithms (GAs) mimic natural selection and can efficiently "evolve" near-global optimal solutions from a large number of alternative solutions. In this paper, GAs are used to optimize gate and vent locations for the resin-transfer molding (RTM) process in order to minimize fill times and dry-spot formation. A process performance index, or cost function, is defined, which incorporates the fill time and dry-spot formation as primary variables. A part having material and geometric complexities was chosen for a case study. GA and mold-filling simulations were used interactively to search for optimal gate and vent locations to locate near-optimal solutions. The GA was able to find good solutions using less than 1% of simulations of the possible permutations of gates and vents. The case study was also repeated in the presence of racetracking channels. Again, the optimal locations were found by the GA using less than 1% of all possible combinations.

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